The 2-Port Shunt-Through Measurement and the Inherent Ground Loop

The 2-port shunt-through measurement is the gold standard for measuring milliohm impedances while supporting measurement at very high frequencies (GHz). These capabilities make it ideal for measuring power distribution network (PDN) impedance both at the circuit and component level. This application note shows how to make a 2-port shunt-through impedance measurement using commercially available vector network analyzers (VNA).

Unfortunately, this measurement includes an undesirable ground loop related to the instrument grounds and test setup cabling. Left uncorrected, the ground loop introduces significant errors. This application note shows how to eliminate the ground loop using the Picotest J2102A or J2113A ground loop breakers. Picotest solutions work with any commercial VNA, oscilloscope, or spectrum analyzer.

Measurement example

The impedance of a known 1mΩ resistor is measured using Bode 100 VNA and Picotest J2102A and J2113A as a function of frequency. A similar approach can be used to measure any PDN impedance, even down to micro-ohms.

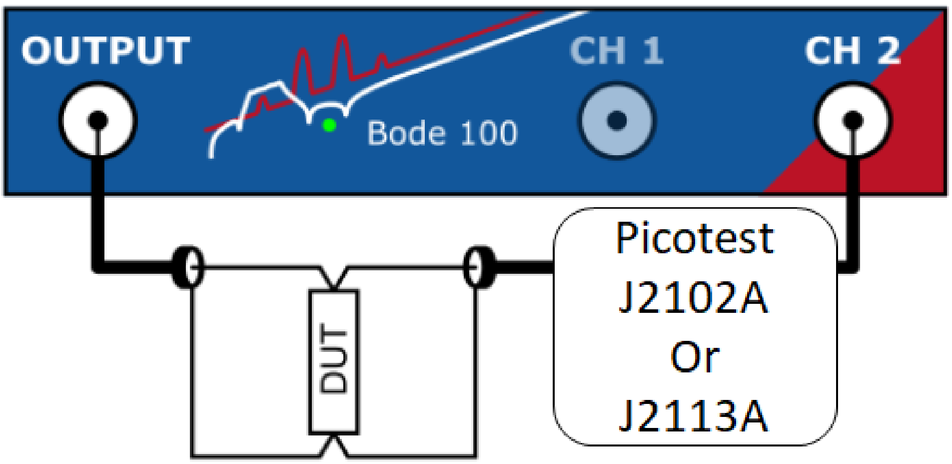

Figure 1: 2-port shunt-through impedance measurement setup using the OMICRON Lab Bode 100 VNA and the Picotest J2102A or J2113A. ZDUT << 50Ω.

Figure 1 shows the measurement setup to measure impedance in the 2-port shunt-through configuration. The setup is valid if ZDUT << 50Ω. The OMICRON Lab Bode 100 is both a 50Ω VNA and a Frequency Response Analyzer (FRA) and is used as a VNA in this application.

Theory of the 2-port shunt-through measurement

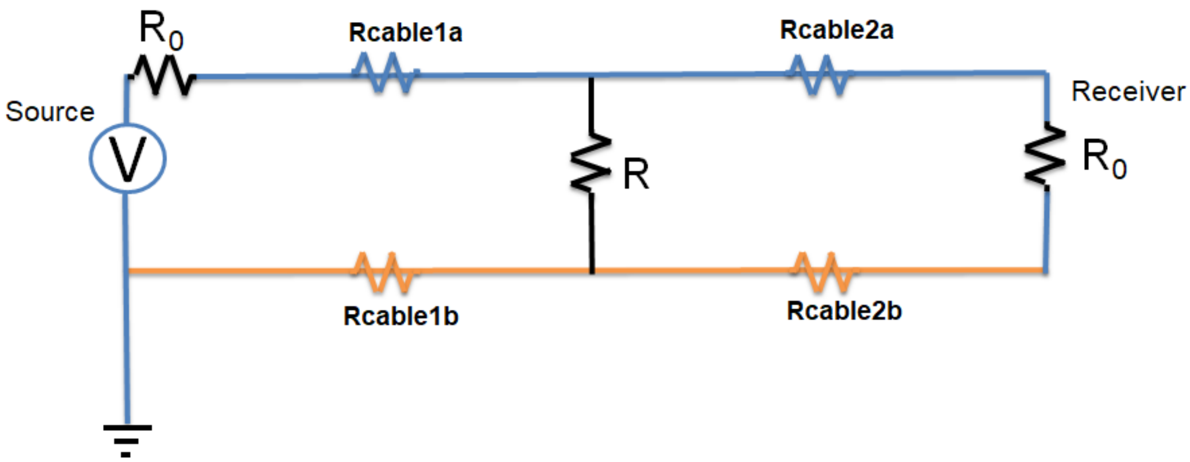

Figure 2: Circuit diagram of 2-port shunt-through measurement to measure an impedance 'R'.

Figure 2 shows the circuit configuration to measure a small valued resistor in the 2-port shunt-through measurement. From the definition of S21 [2, pp. 2-3],

$$S21 \quad = \frac{V_2+I_2R_o}{V_1+I_1R_o} = \frac{2R}{2R+R_o} \tag{1}$$

Solving for R we get,

$$R = \frac{25*S21}{1-S21} \cong 25 * S21 \tag{2}$$

where it is assumed that $R_0 = 50\ \Omega$ and S21 << 1 (True for very small impedance magnitudes or resistances, that is R << R_0). Equation 1 is less intuitive in 2-port shunt-through measurements. Another representation of the definition of S21 is shown in [2, pp. 2],

$$S21 \quad = \sqrt{\frac{\text{Power absorbed by Receiver when R is present}}{\text{Power absorbed by Receiver when R is absent}}} = \frac{2R}{2R+R_o} \tag{3}$$

Equation 3 results in same value for S21 upon simplification. The difference here is that this gives an intuitive feeling for what is happening with S21. The denominator is constant for a VNA, if the source and receiver impedances are fixed. One exception to this is proposed by Steve Sandler in his paper “Extending the usable range of the 2-port shunt-through impedance measurement” [3]. Here the source R_0 is increased to shift the measurement window. Source R_0 is increased to a higher value by adding an external resistor, say, 450 Ω, and the source R_0 now becomes 500 Ω for a 50 Ω VNA; assuming that the frequency range we are interested in is such that the external resistor is electrically very small and is a lumped element at that frequency. What we do here is reduce the maximum power that can be sourced from a VNA, which increases the range of impedances that can be measured. It should be noted that the sensitivity is an inherent property of a VNA and is not changed.

In Equation 3, S21 is the square root of the received power in the Receiver R_0 scaled by the power that could have been received if the DUT was not present. Let us look at the effect of this in 2-port impedance measurements. R = 25*S21, and S21 increases when the received power increases.

Any increase in the received power will be reflected as an increase in R. This is important in understanding the ground loop problem.

Non-idealities and the inherent ground loop

Like all other measurements, the 2-port shunt-through measurement also suffers from non-idealities. Figure 3 shows two non-idealities,

1. Cable losses
2. Ground loop

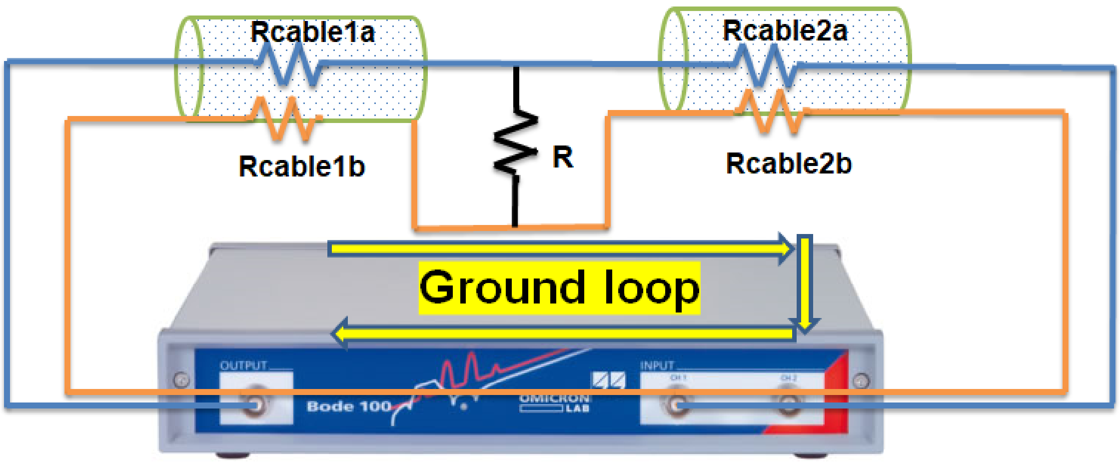

Figure 3: Non-idealities added in the 2-port shunt-through measurements.

Every cable will have cable losses which are marked as cable resistances in Figure 3. Due to National Electrical Code (NEC) requirements for public safety, all grounds in a VNA have to be connected together. This forms a ground loop in the 2-port shunt-through measurement as shown in Figure 3.

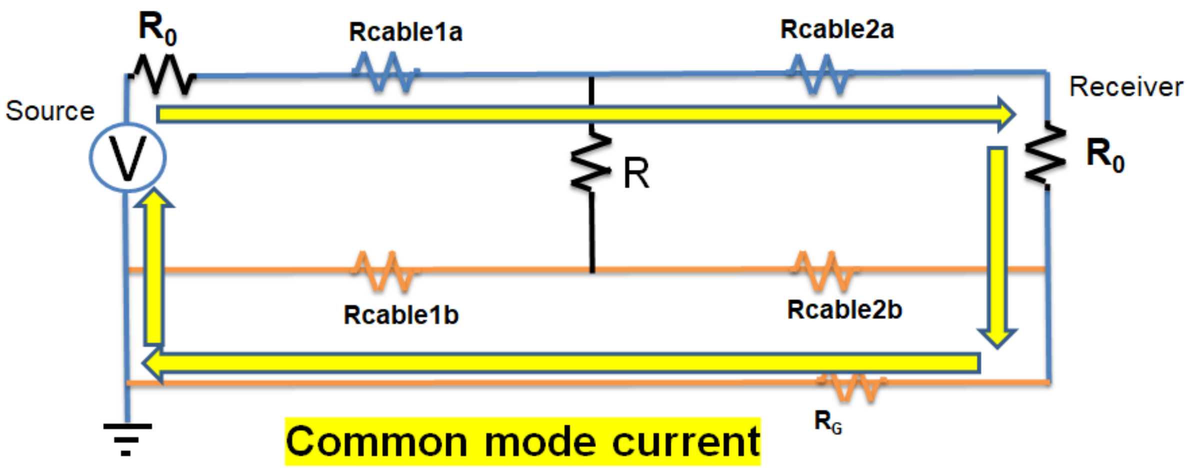

Figure 4: Common mode current formation due to the ground loop.

Figure 4 shows the alternate path for signal current return called common mode current. The addition of ground connections created this path. If this path never existed, all the current would have returned through the cable. The new path created an additional path for current which depends upon the value of R_G. In almost all VNAs, R_G << Rcable1b and Rcable2b. So, the additional current will be much larger compared to the case of not having this additional path. This additional current adds more power in the Receiver which causes it to increase S21 and in turn the estimated R which is 25*S21. This is an error in the measurement and does not relate to the actual value of R. So, this will be treated as an error.

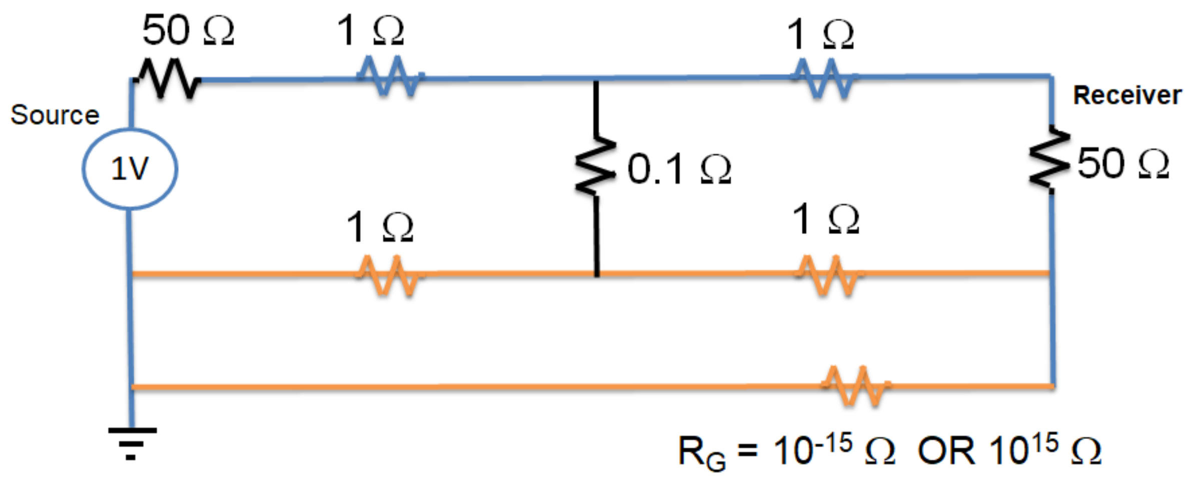

Figure 5: Example to estimate the ground loop error.

Let us take an example to estimate how much error happens from common mode current created by the ground loop. Figure 5 shows an example where the two cases of having and not having a ground loop is studied. A small resistance ($R_G = 10^{-15}$ Ω) is placed in the loop to mimic the ground loop connection and a large resistance ($R_G = 10^{15}$ Ω) is placed in the loop to mimic the ground loop connection. The circuit can be solved with any SPICE program to estimate the power consumed by the receiver in these two cases,

1. $R_G = 10^{-15}$ Ω
2. $R_G = 10^{15}$ Ω

We can use Equation 3 to estimate the S21. The denominator, Power absorbed by the Receiver when R is absent = 5 mW (cable losses are neglected, and it is assumed that there is no port extension through calibration) is the maximum power that can be transferred from the source. This is a constant with respect to a VNA. The S21 for these two cases are,

$$S21 \quad = \sqrt{\frac{2.539751\text{uW}}{5\text{mW}}} = 0.022538$$

$$S21 \quad = \sqrt{\frac{67.861312\text{nW}}{5\text{mW}}} = 0.0036841$$

As we expected in case 1, there is more power consumed by the Receiver due to the higher common mode current. The estimated R from S21 based on R = 25*S21 are,

1. R = 0.56344
2. R = 0.092101

The error due to ground loop is nearly 460%**.** The small deviation in case 2 comes from our approximations and assumptions. The example was done for DC. The same approach can be performed for the AC case too. This is left to the interested readers.

It is clear from this example that we need to minimize the common mode current which contributes a large error in 2-port shunt-through measurements.

Solutions to the ground loop problem

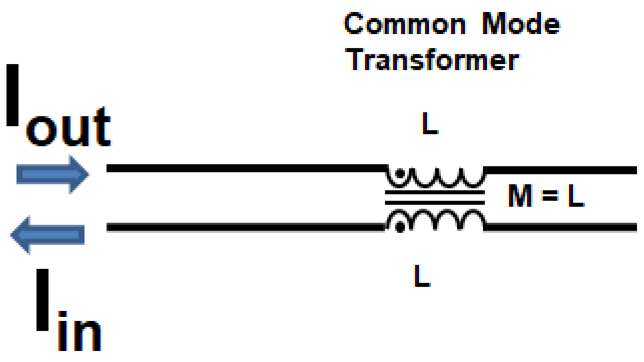

Figure 6: Coaxial transformer circuit.

The obvious way to minimize the measurement error is by minimizing the common mode current. Picotest has two solutions to minimize common mode current:

1. Coaxial transformer - J2102A
2. Semi-Floating Differential Amplifier - J2113A

Coaxial transformer - J2102A

The first solution to the ground loop problem is to introduce a high quality 50Ω common mode transformer or Coaxial transformer. As the name indicates, it blocks common mode current. Figure 6 shows the equivalent circuit of a common mode transformer. The common mode transformer is on a ferrite core such that when $I_{out} = I_{in}$, the inductance offered to the current flow is zero. The part of this current is called differential current. This is the current that contributes to normal operation. When a part of the current flows through one and does not return through the other, it is called common mode current. The common mode transformer shows a very large inductance to this current flow and effectively blocks this. The amount of blocking, known as attenuation, highly depends upon the design of the transformer. Since this transformer should not affect normal operation (VNA measurement operation), it is designed such that the impedance seen by the differential current is 50Ω. An important consideration for the Coaxial transformer is that it is not effective at DC as it is a transformer. Practical measurements show that the Picotest J2102A works at frequencies above about 3 kHz, depending on the cable length and characteristics. The maximum frequency at which the common mode transformer is effective depends upon the core and is determined by the quality of the material. Better measurement results are observed when J2102A is connected in the receiver loop as shown in Figure 7.

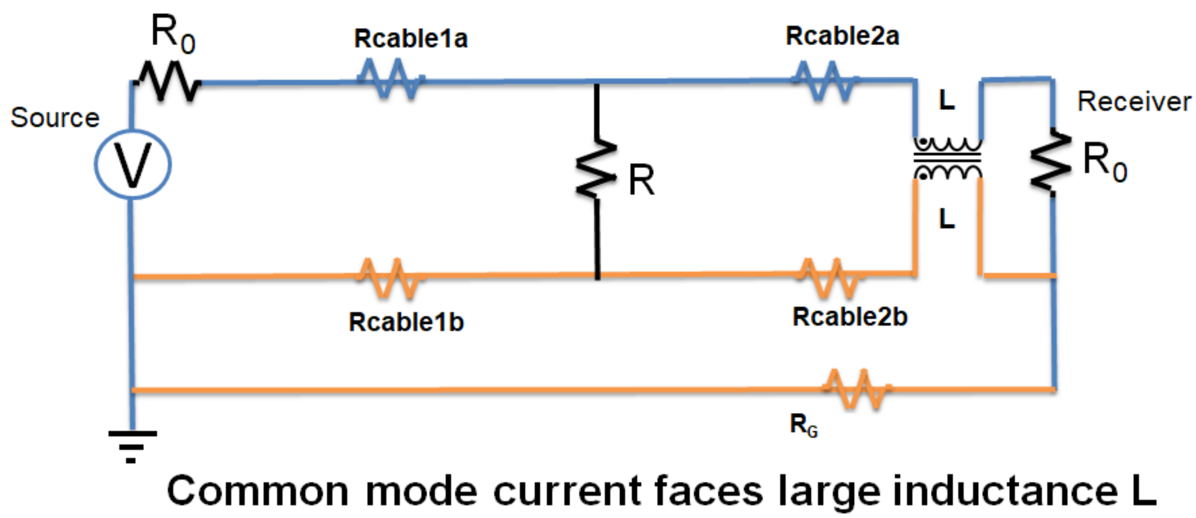

Figure 7: Common mode transformer (J2102A) included in 2-port shunt-through measurement circuit.

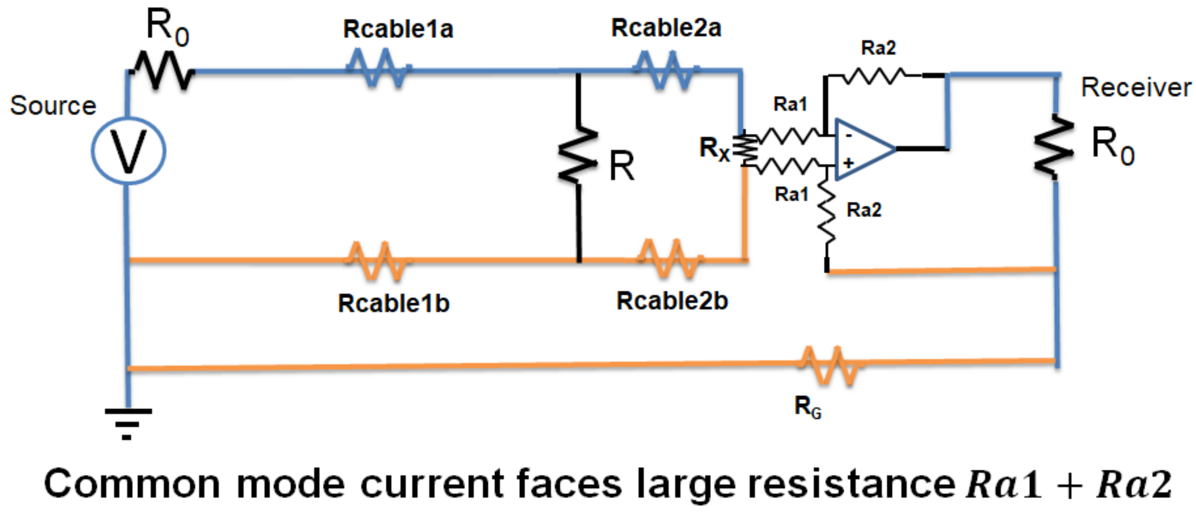

Figure 8: Semi-floating differential amplifier (J2113A) included in 2-port shunt-through measurement circuit.

Semi-floating differential amplifier - J2113A

The second solution to the ground loop problem is achieved by introducing a semi-floating differential amplifier to the test setup. The semi-floating differential amplifier has a large resistance to common mode current. Because of this resistance, the semi-floating amplifier is effective at DC as well. More accurate measurement results, compared with the J2102A, are obtained when the J2113A is connected in the receiver loop as shown in Figure 8.

Making connections

High fidelity measurement requires high quality cables and probes, with high shielding effectiveness. Sometimes it is also important to AC couple the measurement in order to minimize DC loading or if the operating voltage of the measurement might exceed the limits of the VNA. The Picotest PCK01 is a high-performance cable and connector kit while the Picotest P21B01 includes high-quality probes and DC Blocks. The highest accuracy when measuring bulk and decoupling capacitors is achieved by mounting the component on a characterized printed circuit board. The Picotest DTBK01 kit includes most standard sizes and includes de-embedding data to remove parasitics of the PCB from the measurement.

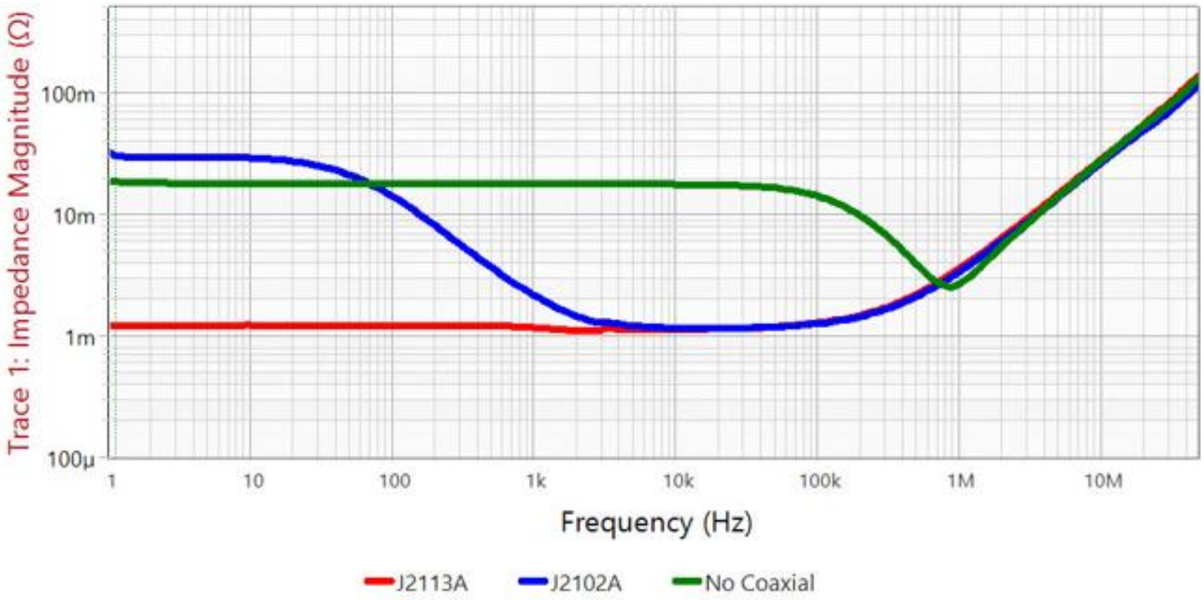

Figure 9: Comparisons of Picotest solutions for ground loop problem in 2-port shunt-through impedance measurements while measuring a 1mΩ resistance.

Figure 9 shows the experimental results comparing the two Picotest solutions and also the measurement without a ground-breaking solution. Figure 10 shows the measured 1mΩ resistance mounted one of the boards included with the Picotest DTBK01 kit. The fixture is de-embedded in postprocessing using the supplied files. Both the Picotest solutions are placed in the receiver loop as shown in Figure 1.

Figure 10: Measured 1mΩ resistance mounted on one of the Picotest DTBK01 test boards.

Conclusion

The Picotest J2102A or J2113A products eliminate the ground loop in any commercial VNA used to measure impedance in the 2-port shunt-through configuration. This ground loop is present in other instruments and test setups and the Picotest products are effective there as well. For additional information and products please visit https://www.picotest.com/measurements/2-port.html.

References

[1] K. Kurokawa, “Power waves and scattering matrix,” *IEEE Trans. Microw. Theory Tech.*, vol. MTT-13, pp. 194–202, May 1965.

[2] R. W. Anderson, “S-parameter techniques for faster, more accurate network design,” *HP applicaton note 95-1*, Feb. 1967.

[3] S. M. Sandler, “Extending the usable range of the 2-port shunt through impedance measurement,” *IEEE MTT-S Lat. Am. Microw. Conf. (LAMC)*, pp. 1–3, Dec 2016.

